Research Paper

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Farmers' preferences for sustainable intensification attributes in sorghum-based cropping systems: evidence from Mali

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Abstract

Sorghum plays a crucial role in the rural economy and nutrition of rural households in Mali. Yet the productivity of this crop is constrained by limited adoption of agricultural intensification technologies, which could be partly because technology development does not properly consider farmers' preferences. This study with smallholder farmers in southern Mali aimed to assess farmers' preferences for different attributes of sorghum technologies through the lens of sustainable intensification. The study used a discrete choice experiment, a method which involves asking individuals to state their preference over hypothetical alternative scenarios, goods or services. We considered six attributes corresponding to different domains of sustainable intensification: grain yield, risk of yield loss, soil fertility, nutrition, labor requirement and fodder yield. We analyzed the data using the mixed logit model, while considering the multinomial logit model as a robustness check. The findings revealed that smallholder farmers are strongly interested in transitioning from their existing sorghum-based cropping systems to those that closely align with these domains of sustainable intensification. However, there were diverse preferences among all the smallholder farmers studied, and between distinct sub-groups of smallholder farmers characterized by their social networks and agroecological zones, which yield relevant policy implications. Overall, these results support the growing research and development prioritization and policy interests toward scaling sustainable intensification among farmers, with a particular focus on human nutrition.

Introduction

Sorghum is the fifth most important cereal globally, with 60 million metric tons harvested in 2010, after maize, wheat, rice and barley with 825, 650, 440 and 150 million metric tons, respectively (Awika *et al.*, 2011). The crop plays a crucial role in Mali's rural economy, where it provides the primary source of income and nutrition in farming communities, contributes to national food security and hence reduces the need for food imports (FAO, 2018). Despite its importance, sorghum is characterized by low yields, estimated at around 1 ton per ha. This is in part due to factors including low and unpredictable rainfall, high temperatures, low soil fertility and pest and disease infestation (Aune *et al.*, 2017); but in addition, farmers' adoption of technologies such as improved varieties and agronomic practices is on average low. This is due to farmers' cash and information constraints and their aversion to risk, and failure by those developing the technologies to consider farmers' preferences, among other reasons (Foster and Rosenzweig, 1995; Dercon and Christiensen, 2011; Lunduka *et al.*, 2012; Magruder, 2018). Because most smallholder farmers produce and consume their produce, both their consumption and production preferences are important for the adoption of sorghum intensification options in Mali (Smale *et al.*, 2018).

Crop intensification options need to be sustainable to increase production while preserving economic benefits, social cohesion and the environment. Sustainable intensification can be defined as increasing crop yield while reducing negative environmental impacts and at the same time enhancing positive ones (Pretty *et al.*, 2011). Empirical studies show that intensification options based on agrochemicals during the green revolution period of technology transfer during the 1960s to 1980s resulted in the deterioration of soil and water quality (Murgai *et al.*, 2001; Ali and Byerlee, 2002). Other studies suggest that during the same period a focus on a few dominant cereals contributed to malnutrition among smallholder farmers and beyond (Welch and Graham, 1999; Pingali, 2012), and a highly skewed distribution of benefits toward some social groups, particularly male and better-off farmers (Hazell, 2009; Pingali, 2012).

To assess the impacts of agricultural development interventions on smallholder farmers, multidimensional approaches are necessary. In this regard, Musumba *et al.* (2017) have developed a sustainable intensification assessment framework (SIAF) incorporating five domains to define and assess sustainable intensification: productivity, economic, environment, human and social domains. The SIAF applies metrics at field, farm, household and landscape levels. It can be used in the assessment of intensification options for cropping systems to provide insights that inform research and development interventions before they are applied in practice (Cassman and Grassini, 2020). In northern Ghana, Kotu *et al.* (2022) assessed the preferences of smallholder farmers for maize technology attributes by drawing on the SIAF.

Several previous studies have focused on selected technology attributes to examine farmers' decisions regarding the uptake of intensification options (Lunduka *et al.*, 2012; Kassie *et al.*, 2015; Ortega *et al.*, 2016; Waldman *et al.*, 2017; Jourdain *et al.*, 2020; Silberg *et al.*, 2020). Other studies of sustainable intensification do not explicitly assess sustainability from farmers' perspectives (e.g., Pretty *et al.*, 2011; Petersen and Snapp, 2015; Waldman *et al.*, 2016; Smith *et al.*, 2017; Snapp *et al.*, 2018).

In this study in southern Mali, we used a discrete choice experiment (DCE), a method which involves asking individuals to state their preference over hypothetical alternative scenarios, goods or services (Train, 2009), to evaluate farmers' preferred sorghum production technologies from a sustainability perspective. This study aimed to assess multidimensional evaluation criteria (as developed by Musumba *et al.*, 2017) for designing and testing technologies for sustainable sorghum production among smallholder farmers in southern Mali, as well as in similar sociocultural and agroecological settings, to support the incorporation of sustainable intensification in agricultural research (Lynam and Herdt, 1989) and its effective prioritization in research and development (R&D) (Cassman and Grassini, 2020). This study also contributes to the growing application of DCE for understanding farmers' preferences for agricultural technologies in the developing country context. Specifically, it is an addition to the few DCE studies in sub-Saharan Africa that consider attribute non-attendance (ANA), where respondents do not consider all the attributes of the alternatives when making their choices, which is a possible source of bias (e.g., Oyinbo *et al.*, 2019).

Study area and methodology

Study area

The study area covers three districts in Sikasso region: Bougouni, Yanfolila and Koutiala (Fig. 1), which fall within two climatic zones, the Sudanian agroecological zone (SAZ) and the Guinea agroecological zone (GAZ). All the villages surveyed in Koutiala are in the SAZ. Most of the villages in Bougouni and all the villages in Yanfolila are in the GAZ. The mean annual rainfall differs, with 889 ± 173 mm in Koutiala, 1126 ± 174 mm in Yanfolila and around 1061 mm in Bougouni. The annual mean temperatures are $28.0 \pm 0.42°C$ in Koutiala, $27.8 \pm 0.48°C$ in Yanfolila and $27.75 \pm 0.5°C$ in Bougouni. In Bougouni district the total land area is estimated to be 20,028 km^2 with a population of 458,546. Yanfolila district covers an area of 9067 km^2 with a population of 212,717 (DNSI, 2009). Koutiala district has an area of 8740 km^2 with a population of 580,453. Bougouni, Yanfolila and Koutiala districts have an average population density of 23, 23 and 66 persons per km^2, respectively, and the

majority live in rural areas. Soils in the three study sites are characterized by an average bulk density of 1.5 g cm^{-3} at 0–20 cm soil horizon and by a weak water retention capacity (Sanogo *et al.*, 2017).

Sikasso region represents 23.24% of the cereal area and 23.11% of the area under sorghum production in Mali. It produces 25.68% of the total sorghum production in Mali, with yields estimated at around 1 ton per ha (INS, 2014). In this region, sorghum is ranked second in terms of production after maize. There are opportunities to develop the sorghum sector in Sikasso region through access to mineral fertilizers, practicing crop–livestock integration and planting improved varieties with high production potential, such as dual-purpose and hybrid varieties, particularly in Bougouni, Yanfolila and Koutiala districts due to the presence there of an Africa RISING research-for-development project (www.africa-rising.net).

Sampling design and data collection

Our sampling framework is based on the list of farm-households interviewed during the Mali Africa RISING baseline survey (MARBES) in 2014. MARBES followed a quasi-experimental design (see Howard *et al.*, 2016 for a detailed description). The sample size was 700 households drawn from 20 villages across the three districts of Sikasso region. Due to resource constraints, in this study we selected 85% of the total sample in MARBES in each village, which resulted in a sample size of 576 households. The research was designed following the DCE survey-based approach described in the following section. Data were collected by trained enumerators based on a structured questionnaire using Computer-Assisted Personal Interviewing software, Open Data Kit.

Design and implementation of the DCE

Three steps were followed to design and implement the DCE. First, relevant attributes were identified through focus groups with farmers and consultations with experts. During the focus group discussions, farmers were requested to list all the attributes they considered important in the sorghum-based cropping system. They were then requested to rank these based on a pairwise ranking technique, which involves matching attributes one-on-one with each other to judge which attribute is preferred overall. After aggregating the lists from the focus groups, discussions were held with collaborating scientists from the International Crops Research Institute for the Semi-arid Tropics (ICRISAT) to make the final selection. Six attributes were selected: sorghum yield, yield stability (risk of yield loss), soil fertility, nutrition, labor requirement and forage yield (see Table S1 for a description of the attributes). These attributes cover four out of the five sustainable intensification domains in the SIAF (Table 1). The fifth domain in the SIAF, the social domain, was captured indirectly through a disaggregated analysis of the data based on the social network of farmers.

In the second step, various attributes and attribute levels were combined to form different pairs of mutually exclusive hypothetical options (choice sets) that would be evaluated by farmers. A Bayesian efficient design was used to minimize the *D*-error and improve the precision of parameter estimates (Rose and Bliemer, 2009). An orthogonal design was generated following Scarpa *et al.* (2013), and a pilot DCE survey was implemented among 41 smallholder farmers based on this design. The pilot
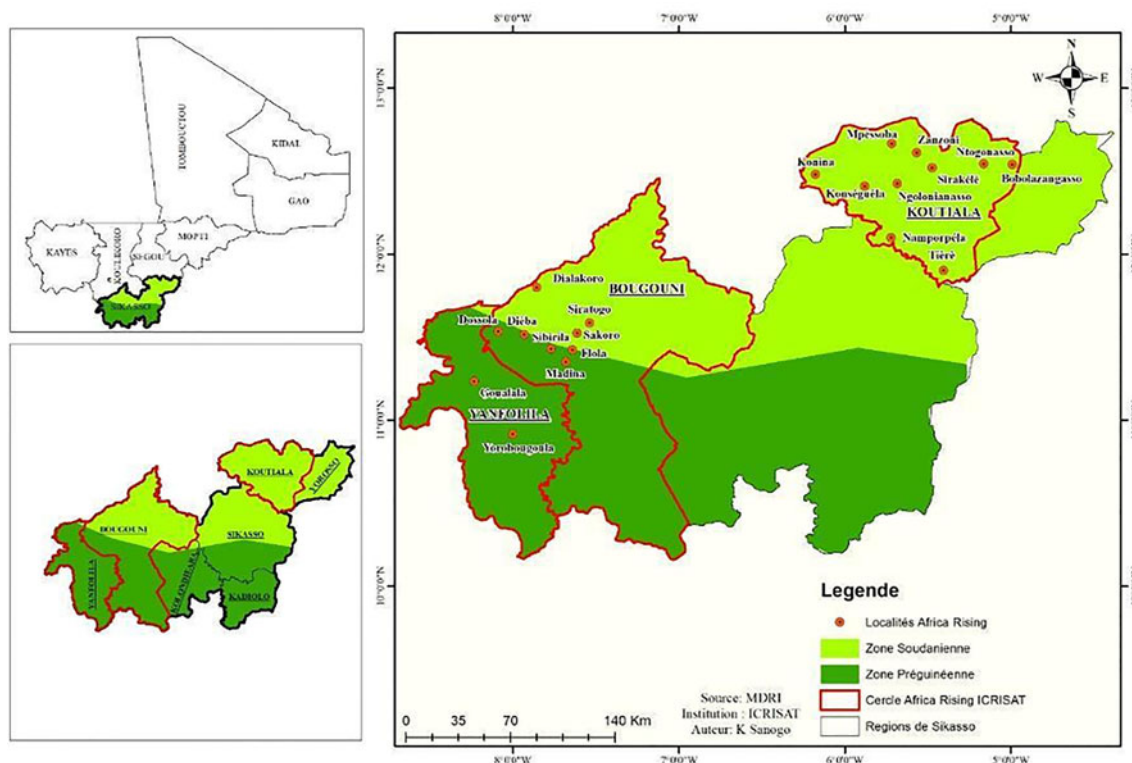
Fig. 1. Map of the study areas.

Table 1. Attributes and attribute levels used in the choice experiment

Attributes	Sustainable intensification domain	Attribute levels
Sorghum grain yield	Productivity	0.5, 1.5, 2.5, 3.5 metric ton per ha
Risk of yield loss	Productivity	0, 25, 50% yield reduction (over 5-year period)
Fodder yield	Productivity	20, 40, 60, 80 cartloads per ha
Soil fertility outcome	Environment	Decrease, neutral, increase
Nutrition outcome	Human	Decrease, neutral, increase
Labor requirement	Economic	20, 30, 40, 50 person-days per ha

data were used to estimate a multinomial logit model, and the parameter estimates were used as Bayesian priors in generating the Bayesian efficient design. Ngene software was used to generate the design, resulting in 12 paired choice sets (D-error = 0.019). The choice sets were randomly blocked into two blocks of six choice sets to make it easier for the farmers to evaluate several choice sets (Hensher et al., 2015). Twelve laminated choice cards were prepared based on the choice sets. Each card consisted of two hypothetical sorghum-based intensification systems (options A and B) and an opt-out (option C) representing the status quo (Fig. 2). Including the opt-out option helps to avoid possible bias associated with forcing farmers to choose option A or B, as farmers should have the option to retain their current practice if they see it as offering more utility than option A or B (Hensher et al., 2015).

Third, the farmers were randomly assigned to one of the two blocks of choice cards, and the DCE was implemented. To

mitigate possible hypothetical bias (Cummings and Taylor, 1999), the farmers received a detailed explanation before commencing interviews during the survey. The explanation included the purpose of the survey, the procedure to be followed, meanings of the attributes and attribute levels and the hypothetical setting of the DCE. Each farmer was presented with six choice cards, one after the other in a random order to avoid ordering effects, and was asked to choose their preferred option between the hypothetical sorghum-based intensification systems (options A and B) and an opt-out (option C). The farmers evaluated the attribute levels of each option on the choice cards and freely made a choice on each of the six choice occasions. This allows us to infer an indirect utility function based on the different attributes and attribute levels of the DCE. At the end of the DCE, the farmers were asked follow-up questions, including attributes ignored, perceptions of the choice tasks and other questions related to the attributes and the DCE in general.
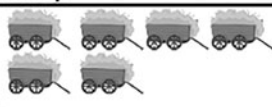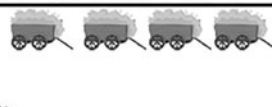
Fig. 2. Example of a choice card used in the choice experiment. Farmers were asked to choose their preferred option between the hypothetical options of sorghum-based intensification systems (options A and B) and an opt-out (option C). Farmers evaluated the sustainable intensification options based on the six attributes (column 1) and their corresponding levels (columns 2 and 3).

Econometric analysis

Discrete choice model estimation

The random utility theory provides the econometric basis for the analysis of discrete choice (McFadden, 1974; Greene, 2008). The theory assumes that the utility of an *i*thfarmer's choice of alternative *j* among hypothetical alternatives of sorghum-based intensification systems offered in choice set *s* is given by an indirect utility U_{ijs}, which consists of observable and unobservable components expressed as:

$$U_{ijs} = V_{ijs} + \varepsilon_{ijs} = \text{ASC} + \sum_{k=1}^{K} \beta_{ik} x_{ijks} + \varepsilon_{ijs} \qquad (1)$$

where V_{ijs} is the observable part of the utility function determined by the selected attributes, and ε_{ijs} is the unobservable part of the utility function, assumed to be independent and identically distributed. ASC is the alternative-specific constant representing preferences for the opt-out option, β_{ik} represents the marginal utility or parameter weight associated with attribute *k* for farmer *i* and x_{ijs} represents the *K* attributes of alternative *j* in choice set *s* faced by farmer *i*. The ASC takes a value of 1 for the opt-out option and 0 for the hypothetical options of sorghum-based intensification systems. A negative coefficient for the ASC implies a positive utility of moving away from the current practice to a more sustainable sorghum-based cropping system. All categorical variables are dummy coded for ease of interpreting estimated parameters.

Two alternative models were estimated. The first one was the multinomial logit model of the form in Equation (1). Multinomial logit is computationally simple to estimate and is considered a good starting point of discrete choice model estimation (Hensher *et al.*, 2015). However, it does not account for unobserved preference heterogeneity, and requires the independence of irrelevant alternatives assumption (Hensher *et al.*, 2015). The second model was the mixed logit model, which accounts for unobserved heterogeneity across farmers by allowing a distribution around the mean values of the preference parameters in Equation (1) (Greene and Hensher, 2003; Train, 2009). The mixed logit model relaxes the independence of the irrelevant alternatives assumption. The parameters of the attributes are assumed to be random following a normal distribution, and the random parameters are uncorrelated. The mixed logit model was estimated separately for the pooled sample and the subsamples of farmers. The consideration of the subsamples in our analysis was to explore heterogeneity in preferences and trade-offs with respect to two policy-relevant variables for intensification: social network and agroecology. The consideration of farmers' social networks allows us to partly capture the social domain of sustainable intensification as described in Musumba *et al.* (2017). Agroecology was considered to capture the heterogeneity in preferences among the sample farmers along the two agroecological zones in Sikasso region, described in the section above on the study area.

Robustness checks

We checked the robustness of our results by estimating another mixed logit model with the assumption that the randomly distributed parameters are correlated. In addition, we estimated two models to account for ANA, a situation where respondents do not consider all the attributes of the alternatives in making their choices (Alemu et al., 2013; Scarpa et al., 2013). This is often considered a potential source of bias for parameter estimates of DCE. Following Caputo et al. (2018), we used self-reported data on attributes that respondents ignored to estimate stated ANA models—both conventional and validation ANA models. In the conventional ANA model, parameters of attributes ignored (τ) by some farmers are constrained to zero in the utility function:

$$U_{ijs} = \text{ASC} + \sum_{k=1}^{K-\tau} \beta_{ik} x_{ijks} + \varepsilon_{ijs} \qquad (2)$$

While the conventional ANA model assumes a zero-marginal utility for an ignored attribute, it is likely that respondents do not completely ignore an attribute, but rather attach a lower weight to it (Hess and Hensher, 2010; Alemu et al., 2013). This motivated the estimation of the validation ANA model, where two parameters are estimated for each attribute, conditional on whether the attribute is reported to be ignored or considered by farmers in making their choices (Hess and Hensher, 2010; Alemu et al., 2013; Scarpa et al., 2013; Caputo et al., 2018; Oyinbo et al., 2020). This model also helps to validate the stated ANA responses of the farmers. The utility coefficients conditional on attendance are denoted with the superscript 1 (β_i^1) and those conditional on non-attendance with superscript 0 (β_i^0) in the utility function:

$$U_{ijs} = \text{ASC} + \sum_{k=1}^{K-\tau} \beta_{ik}^1 x_{ijks} + \sum_{k=1}^{\tau} \beta_{ik}^0 x_{ijks} + \varepsilon_{ijs} \qquad (3)$$

All the models were estimated in Stata software, with the exception of the ANA models that were estimated in NLOGIT. With the exception of the multinomial logit model, all the models were estimated by simulated maximum likelihood using 500 Halton draws.

Results

Descriptive statistics

Table 2 shows summary statistics of farm households' characteristics. Most of the households had a male head, on average 54 years old. A typical household had about 18 members, of whom around 45% were adults. About 28% of the respondents did not attend formal education. About 57% of the households cultivated sorghum solely for food, suggesting that this crop is important for household food security. The average yield of sorghum was about 1 metric ton per ha. Farmers were aware that integrating legumes into their sorghum cropping systems could improve soil fertility (66% of respondents), suppress weeds (58%) and mitigate crop failure (60%). However, fewer respondents were aware of biofortified sorghum varieties (24%), cultivated them (12%) or consumed them in the last 12 months before the survey time (13%). About 57% of the households experienced crop failure at least once in the past five cropping seasons due to bad weather conditions, especially drought. The

average yield reduction was about 27%. Although the perceived crop loss due to crop bad weather is substantial, only about 17% of the households have crop insurance coverage. While households have limited access to institutional services (only 17% have access to extension and cash credit), most of them participate in social groups (69%).

As expected, the households with strong social networks are significantly better off in terms of access to services and institutions, including crop insurance, contract farming, social safety net programs and agricultural advice (Table 2). A significantly higher share of these households with strong social networks is aware of, cultivate and consume biofortified sorghum. In addition, these households have a significantly larger parcel of land, and higher grain yield. On the other hand, a significantly larger share of those households with weak social networks, and a larger share of those households growing sorghum solely for food, experienced a crop failure in the past 5 years. In terms of agroecological typology, households in the SAZ appear to be better off in terms of access to institutional services, such as social groups and weekly markets, than those in the GAZ, while households in GAZ are better off in terms of access to credit in cash. Moreover, the SAZ is better than the GAZ in terms of the percentage of households cultivating sorghum; those who practice sorghum–legume intercropping and those who apply inorganic fertilizer on sorghum plots. While households in both agroecologies are predominantly headed by men, the percentage of households headed by men is significantly larger in the SAZ than in the GAZ. In addition, household heads in the SAZ are older than their counterparts in the GAZ (Table 2).

Econometric results

Choice model results

Estimates of farmers' preferences are presented in Table 3. Except for the coefficient of the risk yield loss attribute, which is significant at the 10% level in the multinomial logit model, the multinomial logit, mixed logit and conventional ANA models produced estimates that are similar in terms of signs and statistical significance of the coefficients. The Akaike information criterion (AIC) and Bayesian information criterion (BIC) values show similarity across the models in terms of fitness. The similarity of the mixed logit and conventional ANA models suggests that the results are robust to potential bias associated with ANA. It is not possible to compare the magnitude of coefficients between models because of scale differences (Greene and Hensher, 2003), so this study makes no claim about similarity in terms of the magnitude of coefficients. The results of the validation ANA model show that farmers' choice behavior in the DCE is not fully consistent with their self-reported ANA behavior, as three parameter estimates of the ignored attributes—grain yield, increased soil fertility outcome and neutral nutrition outcome—are significantly different from zero. This result suggests that farmers who reported that they ignored grain yield, soil fertility and nutrition did not completely ignore these attributes, but they may have assigned lower importance to the attributes in their choice-making processes (Alemu et al., 2013; Scarpa et al., 2013; Caputo et al., 2018) (see Table S2 in the Supplementary materials). Overall, the ANA models do not outperform the standard mixed logit model; hence we focus on the results of the latter model in our discussion.

The ASC coefficient estimate is negative and significantly different from zero, which indicates that on average, the farmers

Table 2. Summary statistics of farmers' characteristics by social network and agroecology

Variable	Full sample	Social network			Agroecology		
		Strong	Weak	t/χ^2	GAZ	SAZ	t/χ^2
Male-headed HH	94%	95%	91%	3.49*	90%	96%	7.44***
Age of HH head	54.35 (13.00)	54.88 (12.53)	52.98 (14.07)	1.57	52.72 (13.03)	55.06 (12.94)	1.97**
HH head has no formal education	28%	31%	19%	8.58***	23%	29%	2.24
Number of adults in HH	8.37 (4.35)	8.76 (4.47)	7.38 (3.85)	3.44***	8.46 (4.45)	8.34 (4.31)	0.31
Number of children in HH	10.40 (9.80)	11.06 (9.88)	8.70 (9.41)	2.60***	9.95 (11.05)	10.58 (9.22)	0.70
Household size	18.77 (12.54)	19.82 (12.65)	16.08 (11.88)	3.23***	18.41 (13.40)	18.92 (12.16)	0.44
HH had crop insurance coverage in the last cropping season	17%	22%	7%	17.33***	17%	17%	0.00
HH participated in contract farming in the last cropping season	14%	17%	5%	14.83***	12%	15%	0.61
HH received support from social safety net programs in the last cropping season	11%	14%	4%	11.04***	9%	13%	1.83
HH is aware sorghum–legume intercropping (SLI) can improve soil fertility	66%	67%	63%	0.90	67%	66%	0.19
HH is aware SLI can suppress weeds	58%	58%	58%	0.001	56%	59%	0.50
HH is aware SLI can mitigate crop failure	60%	62%	53%	4.11***	56%	61%	1.18
HH experienced a weather shock (e.g., drought, flood) over the past 5 years	57%	57%	56%	0.01	56%	57%	0.00
Percentage of yield loss that HH considers a crop failure (above the percentage yield loss perceived to be a crop failure in a normal year)	38.00 (17.38)	36.911 (18.17)	40.75 (14.91)	2.38**	39.56 (16.08)	37.32 (17.90)	1.41
HH experienced a crop failure over the past 5 years	66%	63%	74%	6.48**	64%	67%	0.61
Number of seasons HH experienced a crop failure over the past 5 years	1.34 (1.28)	1.27 (1.26)	1.51 (1.31)	2.00**	1.13 (1.10)	1.43 (1.34)	2.58***
Percentage of crop failure HH experienced over the past 5 years	27.35 (24.92)	25.87 (25.47)	31.10 (23.11)	2.26**	25.20 (24.53)	28.28 (25.06)	1.35
HH grows sorghum solely for food	57%	53%	68%	11.32**	62%	55%	2.18
HH is aware of biofortified sorghum	24%	28%	14%	12.81***	23%	24%	0.07
HH cultivated a biofortified sorghum in the last cropping season	12%	15%	3%	18.57***	12%	12%	0.01
HH consumed biofortified sorghum in the past 12 months	13%	16%	4%	14.79***	16%	12%	1.52
Livestock ownership in the past 12 months	94%	96%	90%	7.94***	92%	95%	1.70
Number of parcels operated by HH in the last cropping season	1.77 (0.93)	1.89 (0.95)	1.46 (0.79)	5.08***	1.80 (0.88)	1.75 (0.95)	0.50
Size of parcel operated by HH in the last cropping season	9.71 (8.02)	10.63 (8.52)	7.38 (5.99)	4.42***	9.38 (8.76)	9.85 (7.68)	0.63
HH owns a parcel	99%	99%	99%	0.02	98%	100%	3.80*
HH cultivated sorghum in the last cropping season	80%	83%	73%	7.59***	58%	90%	76.68***
Share of SLI plots in the last cropping season	24%	24%	23%	0.07	16%	23%	5.25**
Share of sorghum plots with inorganic fertilizer in the last cropping season	35%	35%	37%	0.28	17%	40%	20.81***
Share of sorghum plots with improved seed in the last cropping season	4%	5%	2%	1.65	6%	4%	1.56

Sorghum yield (kg ha^{-1})	964.91 (615.84)	1015.55 (665.45)	815.37 (401.14)	3.22***	926.87 (605.71)	975.13 (617.94)	0.72
HH received agricultural advice in the past 12 months	17%	19%	12%	4.30**	17%	17%	0.02
HH has a member in community's farmer research group	29%	–	–	–	28%	30%	0.17
HH participates in social groups	69%	–	–	–	57%	74%	16.56***
HH received credit in cash in the past 12 months	17%	17%	16%	0.20	22%	14%	5.04**
HH received credit in kind in the past 12 months	12%	14%	9%	2.44	12%	12%	0.00
HH received off-farm income	64%	71%	48%	27.04***	60%	66%	2.00
Distance to the nearest motorable road (min)	9.23 (16.88)	9.28 (16.64)	9.08 (17.52)	0.12	9.16 (17.31)	9.27 (16.71)	0.51
Distance to the nearest weekly market place (min)	30.53 (57.37)	28.52 (55.67)	35.66 (61.36)	1.33	48.87 (88.70)	22.55 (33.21)	5.13***
Observations	576	407	160		172	395	

HH, household; strong social network, HH has a member in community's farmer research group and/or participates in social groups; weak social network, HH has no member in community's farmer research group and/or does not participate in social groups.

Values in parentheses are standard deviations.

***, **, *, variables significant at 1, 5 and 10% levels, respectively.

have positive preferences for sustainable intensification options over their current sorghum-based cropping practice. Farmers prefer options associated with a larger grain yield, a neutral or increased soil fertility outcome, a neutral or increased nutrition outcome and a larger fodder yield. In contrast, options associated with a larger labor requirement are disliked by farmers. However, the latter is only marginally significant in explaining farmers' choices. Surprisingly, the farmers did not place much weight on the risk of yield loss, exhibiting heterogeneous preferences for this attribute. Preference heterogeneity among farmers was seen for most attributes, as suggested by the coefficients of their standard deviations.

Overall, the farmers considered the studied attributes to be important in making decisions about adopting sustainably intensified sorghum-based cropping systems, which suggests that their preferences closely align with the domains of sustainable intensification as described in the SIAF. To explore the relative importance of the attributes, we considered the trade-offs that farmers are willing to make regarding these attributes. The farmers valued grain yield about seven times as much as they valued fodder yield, which suggests that despite the importance of increased fodder yield for livestock production, farmers place more weight on grain yield. This is likely because of the food security role of sorghum, as just over half of households grow sorghum solely for food. Options for sustainable sorghum-based cropping systems with an increased nutrition outcome were valued more than those with a neutral nutrition outcome. The farmers placed substantial weight on increased nutrition outcome—about 25 times as much as they value grain yield. This suggests that farmers are increasingly aware of the importance of nutritional security, beyond the traditional drive for food security. Similarly, an increased soil fertility outcome was valued more than a neutral soil fertility outcome, and the weight placed on increased soil fertility outcome by the farmers was about 21 times the weight placed on grain yield. This suggests that farmers are interested in options that can improve soil health (associated with long-term benefits) over options that can only offer yield gains (associated with short-term benefits).

Observed preference heterogeneity

To allow better insights into preference heterogeneity, and to infer practical implications for fine-tuning sustainably intensified cropping systems and targeting different farmer types, distinct subgroups of farmers are considered beyond the general model results. Table 4 shows that there are notable similarities and differences in preferences between households with strong and weak social networks. Both categories of households exhibited significant positive preferences for grain yield, increased soil fertility outcome, neutral and increased nutrition outcomes and fodder yield, but were indifferent to labor requirement. While households with strong social networks are interested in options with both neutral and increased soil fertility outcomes, households with weak social networks are only keen about options that offer an increased soil fertility outcome. As with the general model results, households with weak social networks appear to be insensitive to risk of yield loss, while households with strong social networks are strongly averse to risk of yield loss. The latter could be a consequence of more awareness within their social networks about the risk of yield loss.

Except for soil fertility outcome, the standard deviations of the estimates are significantly different from zero for households with strong social networks, which suggests preference heterogeneity

Table 3. Results of multinomial and mixed logit models showing farmers' preferences for ANA, with and without control

Parameter	Multinomial logit Mean	Mixed logit Mean	S.D.	ANA Conventional Mean	S.D.	ANA Validation Considered attributes Mean	S.D.	ANA Validation Ignored attributes Mean	S.D.
Alternative-specific constant (ASC)	−2.958*** (0.507)	−3.388*** (0.583)		−3.140*** (0.436)		−3.506*** (0.950)			
Grain yield	0.034*** (0.003)	0.053*** (0.006)	0.055*** (0.006)	0.050*** (0.005)	0.055*** (0.006)	0.057*** (0.007)	0.059*** (0.007)	0.043** (0.021)	0.052 (0.040)
Risk of yield loss	−0.012* (0.007)	−0.014 (0.009)	0.020*** (0.008)	−0.007 (0.006)	0.013 (0.027)	−0.016* (0.009)	0.011 (0.124)	−0.014 (0.012)	0.017 (0.113)
Soil fertility outcome: increase	0.718*** (0.101)	1.133*** (0.172)	0.040 (0.075)	1.190*** (0.142)	0.059 (0.157)	1.141** (0.447)	0.058 (0.277)	1.104** (0.556)	0.109 (0.133)
Soil fertility outcome: neutral	0.261*** (0.049)	0.355*** (0.077)	−0.130 (0.285)	0.364*** (0.007)	0.263 (0.211)	0.360*** (0.086)	0.355 (0.325)	0.520 (0.364)	0.047 (0.037)
Nutrition outcome: increase	0.921*** (0.150)	1.349*** (0.227)	−0.852*** (0.156)	1.523*** (0.154)	0.900*** (0.180)	1.403*** (0.294)	0.923*** (0.324)	0.151 (0.500)	0.923*** (0.324)
Nutrition outcome: neutral	0.625*** (0.065)	0.842*** (0.097)	0.539*** (0.202)	0.822*** (0.097)	0.520*** (0.205)	0.888*** (0.119)	0.550 (0.347)	0.775** (0.323)	0.550 (0.347)
Labor requirement	−0.005** (0.002)	−0.005* (0.003)	−0.017*** (0.007)	−0.005 (0.003)	0.027*** (0.007)	−0.007 (0.007)	0.028*** (0.007)	−0.009 (0.009)	0.0004 (0.002)
Fodder yield	0.003*** (0.001)	0.007*** (0.001)	−0.016*** (0.003)	0.006*** (0.001)	0.015*** (0.003)	0.007*** (0.002)	0.017*** (0.004)	0.006 (0.005)	0.021*** (0.006)
Number of observations	10,206	10,206		10,206		10,206			
Log likelihood	−2055.656	−1975.086		−1987.815		−1970.940			
AIC	4129.311	3984.171		4009.600		4003.900			
BIC	4194.388	4107.094		4113.900		4194.000			

s.d., standard deviation.
Figures in parentheses are standard errors.
***, **, *, variables significant at 1, 5 and 10% levels, respectively.

Table 4. Results of the mixed logit model showing heterogeneity in farmers' preferences by social network

Parameter	Strong social network		Weak social network	
	Mean	S.D.	Mean	S.D.
ASC	−3.449*** (0.618)		−3.574*** (1.279)	
Grain yield	0.052*** (0.007)	0.054*** (0.008)	0.070*** (0.013)	0.070*** (0.012)
Risk of yield loss	−0.021** (0.010)	−0.020** (0.008)	0.003 (0.018)	0.010 (0.014)
Soil fertility outcome: increase	1.238*** (0.215)	0.209 (0.277)	0.901** (0.372)	−0.006 (0.103)
Soil fertility outcome: neutral	0.440*** (0.096)	0.337 (0.261)	0.135 (0.148)	0.096 (0.242)
Nutrition outcome: increase	1.175*** (0.270)	0.886*** (0.209)	2.014*** (0.481)	0.779** (0.344)
Nutrition outcome: neutral	0.900*** (0.122)	0.534** (0.214)	0.818*** (0.198)	0.501 (0.510)
Labor requirement	−0.006 (0.004)	−0.020*** (0.007)	−0.008 (0.007)	−0.011 (0.010)
Fodder yield	0.006*** (0.002)	−0.017*** (0.004)	0.009*** (0.004)	−0.023*** (0.006)
Number of observations	7326		2880	
Log likelihood	−1448.536		−512.949	
AIC	2931.071		1059.898	
BIC	3048.357		1161.312	

S.D., standard deviation.
Figures in parentheses are standard errors.
***, **, *, variables significant at 1, 5 and 10 levels, respectively.

for most attributes. Households with weak social networks exhibited significant preference heterogeneity only for grain yield, nutrition outcome and fodder yield. While both sub-groups placed value on intensification options associated with higher grain and fodder yields, the trade-off between fodder yield and grain yield is on average larger for households with strong social networks. The fodder-yield–grain-yield trade-off suggests that households with strong social networks place more value on grain yield over fodder yield, compared with households with weak social networks. While households with strong social networks placed more weight on increased soil fertility outcome over grain yield, compared with the households with weak social networks, the latter placed more weight on increased nutrition outcome over grain yield compared with the former.

Table 5 shows that there are considerable similarities and differences in preferences for sustainable intensification of sorghum-based cropping systems by agroecological zone. Farmers in both the SAZ and the GAZ had strong positive preferences for sustainable intensification options over their current cropping practices. Those in both categories preferred options associated with larger grain yield, neutral or increased soil fertility outcome, neutral or increased nutrition outcome and larger fodder yield. While households in the GAZ did not place significant value on risk of yield loss, households in the SAZ were significantly averse to risk of yield loss. Households in the SAZ had a negative preference for options associated with an increased labor requirement, while households in the GAZ were not sensitive to labor requirement. Furthermore, households in the SAZ showed strong preference heterogeneity for all the attributes, as indicated by the standard deviations of the estimates. Households in the GAZ displayed heterogeneous preferences only for grain yield, nutrition and labor requirement. While both categories of household preferred intensification options associated with larger grain and fodder yields, the fodder-yield–grain-yield trade-off was on average larger for households in the GAZ. This suggests that households

in the GAZ attached more weight to grain yield over fodder yield, compared with households in the SAZ. However, households in the GAZ placed more value on nutrition as well as soil fertility, over grain yield, compared with households in the SAZ.

Discussion

Our findings show that farmers in southern Mali are strongly interested in transitioning from their existing sorghum-based cropping systems to those that closely align with the domains of sustainable intensification described in the SIAF of Musumba et al. (2017). However, there is considerable preference heterogeneity among farmers in both the full sample of farmers and the sub-samples characterized by social networks and agroecological zones. With respect to the productivity domain of sustainable intensification, farmers are open to sorghum-based cropping systems that are associated with a larger grain yield and fodder yield. This is consistent with previous empirical studies on cropping systems intensification (e.g., Ortega et al., 2016; Waldman et al., 2017; Oyinbo et al., 2019; Silberg et al., 2020). This is expected, given the crucial roles of sorghum grain in crop–livestock farming systems for both household food security and fodder for livestock production, making it a dual-purpose crop in the research area (Waldman and Richardson, 2018).

We found limited evidence to support farmers' risk-averse behavior against yield loss due to weather-related shocks. This finding is not consistent with a growing number of empirical studies suggesting that smallholder farmers are generally averse to yield variability or crop failure (e.g., Jaeck and Lifran, 2014; Coffie et al., 2016; Oyinbo et al., 2019; Jourdain et al., 2020). Our findings could be because of farmers' frequent exposure to weather-related shock, to the extent that they no longer place much value on it, perhaps considering that these factors are out of the control of humans and their institutions (Abay et al., 2017; Taffesse and Tadesse, 2017). It could also be a consequence of less precise attribute levels for risk of yield loss, although

Table 5. Results of mixed logit models showing heterogeneity in farmers' preferences by agroecology

Parameter	GAZ		SAZ	
	Mean	s.d.	Mean	s.d.
ASC	−2.622*** (0.717)		−3.989*** (0.813)	
Grain yield	0.054*** (0.010)	0.060*** (0.010)	0.059*** (0.008)	0.060*** (0.008)
Risk of yield loss	−0.002 (0.014)	−0.018 (0.029)	−0.021* (0.012)	−0.023*** (0.005)
Soil fertility outcome: increase	1.166*** (0.339)	0.025 (0.042)	1.227*** (0.252)	0.334 (0.325)
Soil fertility outcome: neutral	0.178 (0.145)	0.021 (0.058)	0.451*** (0.103)	0.481** (0.222)
Nutrition outcome: increase	1.940*** (0.383)	−0.736** (0.311)	1.218*** (0.324)	1.026*** (0.229)
Nutrition outcome: neutral	0.773*** (0.169)	−0.788*** (0.250)	0.939*** (0.126)	−0.495** (0.231)
Labor requirement	−0.013** (0.006)	−0.021* (0.012)	−0.003 (0.004)	0.018** (0.009)
Fodder yield	0.006** (0.002)	0.005 (0.007)	0.008*** (0.002)	−0.022*** (0.004)
Number of observations	3096		7110	
Log likelihood	−574.144		−1384.514	
AIC	1182.287		2803.029	
BIC	1284.931		2919.806	

s.d., standard deviation.
Figures in parentheses are standard errors.
***, **, *, variables significant at 1, 5 and 10% levels, respectively.

proper care was taken in the choice of attribute levels. More research may help to clarify the role of risk of yield loss in farmers' choices regarding the uptake of sustainably intensified sorghum-based cropping systems.

However, there was substantial preference heterogeneity for risk of yield loss across the farmers; between households with strong and weak networks and between households in the SAZ and the GAZ. These observed differences likely stem from the underlying variation in socio-economic, agroclimatic and market conditions; access to resources and services and institutional setup.

Farmers attached more value to increased nutrition outcome relative to grain yield and other attributes. This supports recent empirical findings in West Africa (Chinedu *et al.*, 2018; Kotu *et al.*, 2022). To gage smallholder farmers' monetary valuation of biofortified crops, Chinedu *et al.* (2018) found that farmers in Burkina Faso are willing to pay for biofortified sorghum varieties. Similarly, Kotu *et al.* (2022) found that smallholder farmers in Ghana showed strong preferences for cropping systems that provide positive nutritional gain. Our finding also lends credence to the growing R&D interventions geared toward improving farmers' dietary protein via sorghum–legume intercropping (Sauer *et al.*, 2018), and toward addressing deficiencies of micronutrients such as vitamins, zinc and iron via biofortification of sorghum (Shikuku *et al.*, 2019; Opata *et al.*, 2021).

With respect to the environmental domain, farmers placed more value on increased soil fertility over grain yield, which is consistent with the findings of previous studies on cropping systems (Waldman *et al.*, 2017; Jourdain *et al.*, 2020; Silberg *et al.*, 2020). This suggests that farmers are interested in sorghum intensification options that can provide long-term benefits (improving soil health) over those options which offer only short-term benefits (grain yields). This finding is consistent for all the sub-groups of farmers considered in our analysis.

With respect to the economic domain, farmers are averse to labor-intensive options, which is consistent with previous studies

(Coffie *et al.*, 2016; Ortega *et al.*, 2016; Oyinbo *et al.*, 2019; Silberg *et al.*, 2020). This suggests that complementary labor-saving technologies may play a role in incentivizing farmers' adoption of sustainable intensification practices. However, farmers' preferences vary across groups and individuals. Specifically, farmers in the GAZ have a strong preference for labor-saving technologies, while farmers in the SAZ have neutral reactions.

Conclusions and policy implications

Our findings show that farmers in southern Mali are strongly interested in changing their existing sorghum production approach in favor of a more sustainable one. This supports the growing R&D prioritization and policy interests toward scaling sustainable intensification among smallholder farmers. Specifically, farmers prefer sorghum production options that increase grain and fodder yields, improve household nutrition, enhance soil fertility and save labor. Their interest in both high grain yield and high fodder yield suggests that sorghum varietal improvement and dissemination efforts should be strengthened toward scaling up dual-purpose sorghum varieties and associated agronomic management practices. Dual-purpose sorghum can make more feed available for livestock, relaxing the livestock feed constraint. However, farmers placed more weight on grain yield than on fodder yield, suggesting that existing and new sorghum breeding programs should not undermine grain yield while improving fodder yield.

Our results also show that farmers placed high value on nutrition-enhancing sorghum technologies. This suggests that R&D and policy interventions among smallholder farmers should go beyond the traditional focus on food security to integrate household nutrition. In this regard, breeding programs for the biofortification of sorghum with different micronutrients could be an appealing option to enhance nutrition. The possibility of integrating legumes into the sorghum system through

intercropping should also be explored, as this approach can increase nutrition while increasing yield through its positive effects on soil health (Silberg *et al.*, 2019; Vanlauwe *et al.*, 2019).

Labor is an important input among smallholder farmers due to limited mechanization for most farming activities. Our findings show that farmers have strong preferences for labor-saving sorghum production options, which suggests that they are very open to production options that enable them to optimize this critical resource. However, farmers are heterogeneous in their preferences for labor requirement, which calls for proper targeting of households based on their labor endowment.

Finally, this study shows that farmers' preferences align with the domains of sustainable intensification as conceptualized in the SIAF. This suggests that integrating multidimensional technology assessment tools such as the SIAF into DCE can help to set evaluation criteria in designing and testing technologies (or a mix of technologies). By enabling researchers to analyze trade-offs and synergies among desirable technology attributes, such tools will be useful to identify sorghum production technologies with high probabilities of adoption among smallholder farmers, thus informing research and policy priorities.

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